ART 34 AMDT

Jns A I

IMPROVED CARBON-CONTAINING MATERIALS

The invention relates to improved carbon-containing materials, methods for their preparation and articles manufactured from them, in particular steel fabrication equipment, electrodes in electrolytic cells used in aluminium production, refractories in high temperature furnaces and other engineering products.

Carbon bonded composite materials are finding increasing use as replacements for traditional ceramic composites. Such replacement usually results in greatly improved properties and processing ability. Examples can be found in a wide range of industries which include those manufacturing refractory products such as steel fabrication equipment and electrolytic cells used in aluminium production.

In the preparation of carbon bonded composites, an organic polymer phase is converted to a type of carbon during heating which usually progresses through various temperatures of up to 2000°C. These composites also generally contain carbon black fillers which are added to control rheological properties, assist in processing or improve mechanical properties. The physical state of the carbon may vary from fine particles to fibers and platelets.

Although this practice has been adopted for many years, the effect of carbon black on the organic polymer phase formation during curing and the carbon structure produced during pyrolysis has received little or no attention. We have now found that carbon black has a significant impact on the final formation of the carbon material from the polymer. In general, the porosity of the carbon material derived from polymer resin will increase when more carbon black is added. This porous structure results in low density and sub optimum mechanical properties. We have also found that other carbon sources such as pulverized graphite or carbon derived from pyrolysis of phenolic resins exhibit similar effects to carbon black.

Mesophase carbon was developed in the last few years for the purpose of making graphitic carbon at relative low temperatures of 2000 to 2500°C. Mesophase carbon may be derived synthetically from aromatic hyrdocarbons or

from petroleum pitch. Synthetic mesophase which can be derived from aromatic hydrocarbons such as naphthalene consists of up to 100% anisotropy, while mesophase derived from petroleum pitch usually has only up to 75% anisotropy. Synthetic mesophase was developed as a superior precursor to graphitisation and

5   is extensively used in carbon fiber applications. Such materials are usually used as a binderless mould and application temperatures are generally more than 2000°C.

We have now found that when synthetic mesophase carbon derived from aromatic hydrocarbons is used as a filler in combination with an organic polymer binder that carbon materials having unexpected and improved properties are

10   obtained. These carbon materials generally have a low porosity measured as a low surface area, high carbon yield, high composite density and good mechanical properties.

According to one aspect of the present invention there is provided a composition suitable for the preparation of a carbon-containing material including:

15   (i)   a binder phase containing an organic resin component or a polymer composite;

           (ii)   synthetic mesophase carbon derived from aromatic hydrcarbons; and

           (iii)   optionally filler particles.

20   According to another aspect of the present invention there is provided a method for preparing a carbon-containing material including the steps of:

           (a) mixing a binder phase containing an organic resin component or polymer composite with synethetic mesophase carbon derived from aromatic hydrocarbons and optionally filler particles;

25   (b) curing the mixture; and

           (c) heating the cured mixture.

The term "organic resin component" is used herein in its broadest sense to denote low molecular weight polymerisable entities through to higher molecular weight entities containing many repeat units. The term includes monomers,

30   dimers and oligomers.

-3-

A wide range of resin structures are possible but generally this structure will be dictated by resins with a low number of heteroatoms and high carbon content. Suitable resins are those of the formulae (I) and (II) respectively:

$$R - XH \qquad\qquad (I)$$

$$POLYMER - R - XH \qquad\qquad (II)$$

wherein X is oxygen, sulphur or nitrogen and R is aryl, imidoaryl, alkyl, alkenyl, alkynyl or heterocyclyl which may be optionally substituted.

In this specification "optionally substituted" means a group that may or may not be further substituted with one or more groups selected from alkyl, alkenyl, alkynyl, aryl, halo, haloalkyl, haloalkenyl, haloalkynyl, haloaryl, hydroxy, alkoxy, alkenyloxy, alkynyloxy, aryloxy, carboxy, benzyloxy haloalkoxy, haloalkenyloxy, haloalkynyloxy, haloaryloxy, nitro, nitroalkyl, nitroalkenyl, nitroalkynyl, nitroaryl, nitroheterocyclyl, azido, amino, alkylamino, alkenylamino, alkynylamino, arylamino, benzylamino, acyl, alkenylacyl, alkynylacyl, arylacyl, acylamino, acyloxy, aldehydo, alkylsulphonyl, arylsulphonyl, alkylsulphonylamino, arylsulphonylamino, alkylsulphonyloxy, arylsulphonyloxy, heterocyclyl, heterocycloxy, heterocyclylamino, haloheterocyclyl, alkylsulphenyl, arylsulphenyl, carboalkoxy, carboaryloxy, mercapto, alkylthio, arylthio, acylthio and the like.

Organic resins components having hydroxyl groups such as those of the formulae (I) and (II) above wherein X is oxygen and R is optionally substituted aryl, for example, phenolic resins or substituted phenolic resins are preferred. Suitable phenolic resins include phenol-aldehyde type resins such as phenol-formaldehyde type resins, for example, resole or novolac and phenolic imide or phenolic polyimide. It will be appreciated that the phenolic resins may be substituted with any non-deleterious substituent including alkyl, for example, methyl or t-butyl; or imide, for example, maleimide or succinimide.

The desirable composite will have a heteroatom, such as nitrogen in the system from polymer or crosslinker or solvent. This can be done by using an organic binder having nitrogen, such as polymide; crosslinker, such as HMTA; or a solvent, such as pyridine.

The term "polymer composite" is used herein in its broadest sense and refers to the combination of an organic resin component with another material, such as, for example, other polymers, particulate matter and/or additives known in the polymer art. It will be appreciated that one or more of the other materials may
5   be inert or chemically reactive. The polymers may be selected from those defined above and can be in the form of a solution, dispersions, fibers or particles. The additives may include crosslinkers such as hexamine which is also known as hexamethylene tetramine (HMTA), polymerisation promoters, catalysts, soaps, wetting agents, accelerators, hardeners and sources of formaldehyde such as
10   formalin, paraform or trioxane. Suitable polymer composites include novolac-HMTA, novalac-furfuryl alcohol(FA)-HMTA, resole-novolac-HMTA, resole-carbon, resole-carbon-novolac-HMTA-FA,novolac-HMTA-FA-carbon, novolac-HMTA-FA-carbon-TiB$_2$,   resole-carbon-alumina-silica,   carbon-TiB$_2$-resole, imidophenol-HMTA,   poly(N-(hydroxyphenyl)   maleimides)-HMTA   and
15   polyimide-novolac. A preferred polymer composite is novolac-FA-HMTA.

The mesophase carbon can be in the form of fibers, pellets, platelets or powder. The powder form can be obtained by pulverising the mesophase in a ball mill. As discussed above, the mesophase may be derived synthetically from aromatic hydrocarbons such as naphthalene. Examples include 100% anisotropic
20   mesophase derived from naphthalen. The 100% anisotropic naphthalene may be prepared by cationic oligomerisation catalysed by HF/BF$_3$. The mesophase may be untreated or pre-treated by heating generally up to about 600°C.

The selection of filler particles largely depends upon the intended use of the carbon containing material. Examples of particulate matter include coated or
25   uncoated fibers, platelets, pigments, fillers, polyesters, metallic mesh, silicon oxides, graphite, carbon black, carbides or nitrides and inorganic material such as aluminium, magnesia, zirconia, bauxite, clay, alumina, titanium diboride, zirconium diboride or titanium oxide. For instance, the inclusion of titanium diboride fillers provides a carbon material which can be used as a wetted cathode
30   in advanced aluminium reduction cells.

The organic resin component, polymer composite and/or mesophase carbon may be presented in the form of a slurry, suspension or dispersion. The solvent used in the slurry, suspension or dispersion can be inert or chemically reactive and may contribute to the properties of the organic resin component or polymer composite. It is often advantageous for the solvent or its reaction products to be incorporated into the polymer derived carbon. This also reduces the loss of weight of the organic resin component or polymer composite on curing. The choice of solvent will depend on the type of organic resin component, polymer composite and/or mesophase carbon employed. An example of such a solvent is furfuryl alcohol. Other solvents include water or organic solvents such as aromatics, for example, toluene or benzene; ketones, for example, methyl ethyl ketone; alcohols, for example, FA or glycol (G); esters; ethers, for example, tetrahydrofuran (THF) or dioxane; or mixtures thereof.

Other additives known in the polymer art such as those defined above may also be included in the organic resin component, polymer composite and/or mesophase carbon mixture. In a preferred embodiment, the mesophase carbon is combined with a solution of novolac/HMTA/FA.

The binder phase may be mixed with the mesophase carbon in step (a) of the method of the invention using any suitable known apparatus, such as, for example, an Eirich mixer. The mixture of the binder phase and the mesophase carbon is generally cured at temperatures up to about 205°C. Curing is normally carried out under atmospheric pressure but can employ vacuum assistance or use elevated pressure in autoclaves to either draw off or retain more volatile species in specific mixtures. The cured mixture is then heated or pyrolysed in step (c) at temperatures sufficient to carbonise the material to a suitable form. This occurs at temperatures above about 800°C but higher temperatures may be employed to further improve the structure and chemical stability. In certain applications, the final temperature can be as high as about 2000°C. The choice of temperature in part depends on the composition and properties of any filler particles, and on the desired end use.

-6-

The carbon-containing material of the present invention has many desirable properties including controlled surface area, high density, good mechanical strength, Strain to Failure (StF) values and anti-corrosion properties. For example, the carbon-containing material may have a total surface area of 20 m²/g (Langmuir

5 method) which gives excellent anti-corrosion, a high mechanical strength of about 60 MPa after curing and about 58 MPa after heating, a high carbon density of more than about 1.4 g/cm³ and improved oxidation resistance with the oxidation temperature under O_2 being higher than about 570°C.

These desirable properties enable the carbon-containing material of the

10 present invention to have various industrial applications. High performance carbon materials having anti-corrosion properties are often required by the refractory industry to form cathodes in aluminium reduction cells or bricks in steel making vessels. On the other hand, good mechanical and anti-oxidation properties of carbon materials are important in the products used in steel processing.

15 Thus, the present invention also extends to articles manufactured from the carbon-containing material, made from ferrous and non ferrous materials, glasses and ceramics, for example, steel fabrication equipment such as slide gates or valves, tap hole blockers and blast furnace linings, electrolytic cells used in aluminium production and other engineering products such as thermal protection

20 barriers, aerospace components and aircraft, satellite and space craft structures.

The method used to prepare the carbon-containing material of the present invention is simple and the precursors of the binder phase and the mesophase carbon are commercially available and cheap. Accordingly, the present invention has the capability of producing a high performance material in an efficient and

25 economical way.

The invention will now be described with reference to the following examples. These examples are not to be construed as limiting the invention in any way.

In the examples, reference will be made to the accompanying drawings in

30 which:

Figure 1 is a graph showing a comparison between the surface areas of carbon materials containing mesophase and carbon black;

Figure 2 is a graph showing a comparison between the densities of carbon materials containing mesophase and carbon black;

Figure 3 is two graphs showing a comparison between the maximum strength of carbon materials containing mesophase and carbon black after (a) curing and (b) heating;

Figure 4 is six scanning electron microscope (SEM) images of composites having resin and (a)-(c) carbon black and (d)-(f) mesophase;

Figure 5 is three graphs showing (a) pore size distribution of carbon made from 100% polymer after pyrolysis to 1000°C, (b) pore size distribution of carbon made from 50% CB in polymer after pyrolysis to 1000°C and (c) pore size distribution of carbon made from 50% MPN in polymer after pyrolysis to 1000°C; and

Figure 6 is a graph comparing carbon densities from composites made using an additive of carbon black (CB) and mesophase (MPN) in a material containing titanium diboride filler particles.

EXAMPLE 1

A mesophase pitch synthesised from naphthalene by catalytic reduction with HF/BF₃ is pre-heated under constant argon flow (7 ml/min). The pre-heating program used was 50°C/h to 500°C, keeping at that temperature for 1 hour followed by further 50°C/h to 600°C. The pre-treated mesophase was then pulverised with a ball mill for 1 min into powder before being blended with novolac resin with HMTA as the crosslinker in the solvent FA. The ratio of novolac/HMTA/FA was 40/8/52. Various samples with different ratios of resin and mesophase were prepared using this method and subsequently cured to 205°C over approximately 30 hrs at atmospheric pressure.

The cured composites were then pyrolysed to 1000°C at a rate of 50°C/h under an argon flow at 7 ml/min. The carbon-containing material produced was subsequently pulverised into a grain before various property tests were conducted.

Figure 1 shows the surface area of these carbon samples compared with samples prepared using the same methods, but where the mesophase was replaced by carbon black (CB). The surface area was obtained by measuring with N_2 at 77 K using a Langmuir Equation. The results show that, unlike the carbon black as a 5   filler, the mesophase/resin system produces a low porosity carbon-containing material.

EXAMPLE 2

The pre-treated mesophase obtained in Example 1 was mixed with a 10   novolac/HMTA (40/8 in ratio) resin powder in various amounts. 1 g of each mixed sample was then cold moulded into a block having the dimensions of 13 mm in diameter and 5-6 mm in thickness. The pressure used in moulding was 400 kg/cm^2. The blocks were then cured and carbonised as described in Example 1. The bulk densities of the blocks after moulding, curing and carbonisation were 15   calculated by measuring their dimension and weight.

Figure 2 shows that final carbon densities are higher with resins blended with mesophase compared to those blended with carbon black produced in the same way. Such high density results in a high strength in the mechanical tests as shown in Figures 3a and 3b. After curing, the maximum strength of the blocks 20   were similar in the range of additive to about 70 to 90% with both mesophase and carbon black derived blocks. However, pyrolysed blocks in the same range have a much higher maximum strain when mesophase is blended with the resin. The carbon black blended carbon material has a poor mechanical strength after pyrolysis.

25   The surface area measurement of the samples pulverised from the blocks resulted in the similar effects observed in Example 1.

EXAMPLE 3

The effects of carbon material derived from other sources, but not 30   mesophase were also tested with a novolac resin. The novolac/HMTA/FA system described in Example 1 was blended with 50% of carbon powder pulverised from

other carbon sources. These carbon sources include pulverised graphite, carbon obtained from the pyrolysis of pure novolac/HMTA/FA to 1000°C and carbon of the same pure resin after pre-treatment using the profile described in Example 1. The resulting mixtures were then cured and pyrolysed to 1000°C as described in

5 Example 1. Table 1 shows that these carbon sources have similar effects to carbon black on the porosity of the final formed carbon/carbon composite.

Different types of mesophase were tested under the same conditions and the results are shown in Table 1 below. The other mesophase carbon used was mesophase derived from naphthalene without pre-treatment. Table 1 indicates that

10 this mesophase carbon has a similar effect on the porosity of the final formed carbon materials as the pre-treated mesophase. The pyrolysis weight loss is also much higher.

Table 1.   Effect of other carbon fillers on the carbon material formation from
15   a novolac/HMTA/FA mixed system

	50% Carbon Black	50% pre-treated mesophase	50% graphite	50% resin carbon	50% pre-treated resin	50% un-treated mesophase
Cure Weight Loss (%)	11	12	10	19	12	11
Pyrolysis Weight Loss (%)	18	25	19	25	21	35
Surface Area (m²/g)	266	33	46	266	215	12

20

EXAMPLE 4

The novolac/HMTA/FA system described in Example 1 was blended with 50% carbon black or 50% treated mesophase powder pulverized by a ball mill method. The composites formed with this method were then cured and pyrolysed to 1000°C as described in Example 1 being subjected to scanning electron microscopy (SEM) as shown in Figure 4. Figures 4a to 4c are the SEM images of the composite having 50% carbon black resin with different amplification. Figures 4d to 4f are the equivalent images of the composite having 50% mesophase and resin. As shown in the figures, the images with resin/carbon black composites appears as a non-homogeneous form where the carbon black powder can be clearly identified. On the other hand, the image of the block from the resin/mesophase composite gives a uniform material, indicating a strong interaction between resin and mesophase during curing and pyrolysis.

EXAMPLE 5

The novolac/HMTA/FA system described in Example 1 was blended with the powder of 50% carbon black (CB) or 50% mesophase (MPN), respectively. These powders were made by pulverization within a ball mill. The formed composites, together with pure resin, were cured and pyrolysed to 1000°C as described in Example 1. The resultant carbon and carbon composites were degassed under an argon flow at 400°C for 48 hours followed by full isotherm adsorption measurements with nitrogen at 77 K using a ASAP 2010 surface analyzer. A DFT plus software supplied with the analyzer then calculated the measured full isotherm curves to provide the pore size distributions. Figure 5 shows the pore size distributions calculated from these tested samples.

The carbons derived from pure resin polymer gave a low surface area of 21 m^2/g and no significant micropores appeared in the distribution, as shown in Figure 5(a). However, when 50% carbon black was mixed with the resin, the measured surface area increased to 266 m^2/g as shown in Table 1 above and this porosity is mainly contributed by micropores (8-10 Å pore width, Figure 5(b)). Assuming that the low surface area carbon black (~10 m^2/g) did not become

porous during the pyrolysis based on the results in Figure 1, the huge porosity
from the composites with CB was obviously due to the effect of adding carbon
black to the resin polymer during its carbonization. When 50% MPN was used,
this additive did not create any significant micropores in the carbons derived from
5   polymer (Figure 5(c)). Therefore, using MPN to replace CB as an additive in the
composite avoids the formation of micropores in carbon derived from polymer.

EXAMPLE 6

Two types of cement were formed by mixing of 24% of novolac, 34% of
10   furfuryl alcohol, 4.6% of HMTA and 37.4% of two different additives: carbon
black and mesophase, respectively. 6.5% of each of these two cements was then
mixed, respectively, with 93.5% titanium diboride (TiB$_2$). Two batches of 5.1 kg
of each mixture were then compacted in a vibroformer make a lab block of the
size about 150 x 150 x 60 mm. The pressure used to compact the block was
15   standard pressure of 200 psi x 50 followed by vibration forming at ~ 100 psi. The
densities of the formed lab blocks and their saturation values are given in Table 2
below.

Table 2. Physical data of tested lab blocks after compaction and pyrolysis

Sample Name	CB1	CB2	MPN1	MPN2
Density after compaction (g/cm^3)	3.45	3.54	3.52	3.52
Saturation after compaction (%)	90.0	92.4	91.8	91.8
Shrinkage after pyrolysis (%)	0.03	-0.19	-0.35	-0.31
Weight Loss after pyrolysis (%)	1.95	1.95	2.27	2.30

20

These blocks were then cured to 205 °C in an oven, and pyrolysed to
1000 °C while the blocks were packed in petroleum coke. The total weight
losses after pyrolysis were similar for both types of composites and there was no
obvious size shrinkage observed from these blocks (Table 2). However, the

-12-

density of the carbon composite made with MPN as an additive has a value of 3.44 g/cm^3 compared with the value of 3.38 g/cm^3 of the composite using carbon block as an additive (Figure 6).

5   **EXAMPLE 7**

Each of the 4 lab blocks of the carbon composites obtained in Example 6 was cut in half and then sectioned into 6 strength bars having a size of 25 × 30 × 150 mm. These bars were then subjected to a three points bend test. Table 3 below gives the results from these mechanical tests.

10

Table 3.   Mechanical test results from 3 points bend test for the composites made using CB and MPN as additives

Samples	CB	MPN
Strength (MPa) (average of 8 bars from the center of the composite)	2.71	6.57
Young's Modulus (MPa) (average of 8 bars)	715	1630
Strain to Failure (StF) (%)	0.38	0.40

The results show that the composites made using MPN as an additive have approximately double the mechanical strength of the composites using CB as an additive. This result is in agreement with the result of the composites formed by polymer/additive only system (Example 2).   The Young's Modulus of MPN sample also increased from 715 to 1630 MPa compared to the CB sample. Although the Young's Modulus has increased, the Strain to Failure of MPN sample has also increased from 0.38 % to 0.4 % highlighting the improved mechanical properties.

EXAMPLE 8

The lab blocks of carbon composites obtained in Example 6 were cut into the standard size of 25 × 30 × 150 mm and then subjected to compression tests. Table 4 below shows the results of these tests.

Table 4. *Mechanical test results from compression test for the composites made using CB and MPN as additives*

Samples	CB	MPN
Strength (MPa) (average of 6 samples)	11.9	25.8
Young's Modulus (MPa) (average of 6 samples)	1057	1720

5   Similar to the observation in Example 7, the mechanical strength of the MPN sample is 2.5 times stronger than the sample of CB. The Young's Modulus also increased from 1057 to 1720 MPa.